

# REDUCTION BEHAVIOUR OF FIRED IRON ORE PELLETS

*A thesis submitted in partial fulfilment of the requirements for the*

*degree of*

**Bachelor of Technology**

**In**

**Metallurgical and Materials Engineering**

Under the Guidance of

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**ROURKELA**

**CERTIFICATE**

This is to certify that the thesis entitled “**Reduction Behaviour of Fired Iron Ore Pellets**” submitted by Mr **Arpit Trivedi** and Mr **Sourabh Seth** in partial fulfilment of the requirements for the degree of Bachelor of Technology in Metallurgical and Materials Engineering at National Institute of Technology, Rourkela [Deemed University] is an authentic work performed by them under my supervision and guidance. To the best of my knowledge and belief, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any degree or diploma.

**SUBMITTED:**

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## ABSTRACT

The present project work on- “**Reduction Behaviour of Fired Iron Ore Pellets**” was undertaken with a vision to promote the effective utilization of iron ore and coal fines in sponge iron making. Presently, India has become the world leader in sponge iron production and the production of steel by DR-EAF route is increasing day by day. In the present project work, the effect of addition of concentrated Sucrose binder on the physical properties of fired iron ore pellets was investigated. The crushing strength was found to be maximum at 2% binder addition, followed by a decrease with further increase in binder concentration. A reverse trend was observed in the case of porosity, i.e. porosity of fired pellets increased with rise in binder concentration from 1% to 8%. The pellets fired at 1100 C were treated for reduction studies in different types of coal. The degree of reduction of fired iron-ore pellets increased with increase in reduction temp and time up to the range studied. The degree of reduction of fired pellets was found to be increasing with increase in the reactivity of the coal.

# INTRODUCTION

It doesn't matter wherever we are, if we stop for a while and focus we would be able to know that we are surrounded with various types & grades of steel. In fact we can't even imagine our life without it. May it be a small knife to cook food or our homes where we live, starting from small a coin to massive automobiles, Steel is everywhere. From the ages of Sword's Smiths to Modern day engineering various types of steels and their method of preparation have been developed.

As India proceeds towards higher levels of growth and greater and more concentrated efforts in the improvement of Infrastructure and manufacturing area, the Iron and Steel industry is self-assured for a quick growth in the upcoming years. Steel demand in the country is snowballing at the rate of 11 % and is likely to remain in the equivalent range at least for the next 14-15 years. In order to meet this unremitting growth of Steel demand in the country, domestic Steel producing capacity is essential to be higher than 140 MT per annum by 2017.

Though primarily iron production is mostly through the blast-furnace route. Though, disadvantages integrated to the blast\_furnace process such as: (1) dependency on high-quality metallurgical grade-coke; (2) Economic viability only at large capacities; (3) environmental constraints; (4) requirement of auxiliary plants; and (5) high investment and operational intensity, headed to development of alternative iron making processes such as the mini blast furnace process, smelting reduction routes, and direct reduction routes. In contrast, direct reduction processes include reduction of iron oxides in the solid state, lower than the fusion temp of pure iron (1534°C), employing hydro-carbon gases and or carbon bearing materials as reducing-carburizing agents.

It's obvious that, any gaseous medium is not required to operate the real DRI. But now it has been well acknowledged that, the reduction of Iron-oxide by Carbon in blast furnace and direct reduction procedure of sponge Iron production is mostly the consequence of indirect reduction. Currently a lot of prominence is being given to direct reduction process because use of pre-reduced pellets or sponge iron as feed for blast-furnace induction-furnaces & basic-oxygen furnaces, in spite of of some associated disadvantages, provides ample scope for refining both economy and productivity in coke intake.

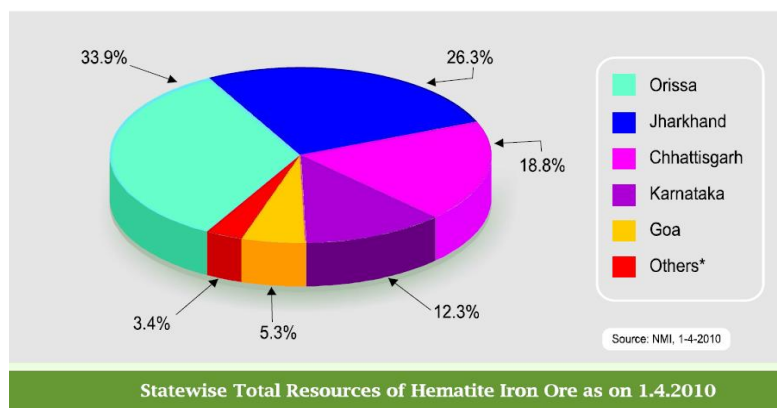
## Iron Ore Reserves of India <sup>[3] [4]</sup>

Iron ore reserve estimates for world is around 170 billion tonnes with average iron content of 47%. India has the sixth largest reserves of iron ore in the world, and these are some of the best quality iron ore reserves in the world. India along with Ukraine, Russia, China and Australia accounts for about 75% of the world reserves. Indian resources of iron ore according to UNFC system as on 1.4.2010 are estimated as 28.53 billion tonnes.

The details of state-wise distribution of iron ore reserves in India are given in Table 1 & Figure 1.

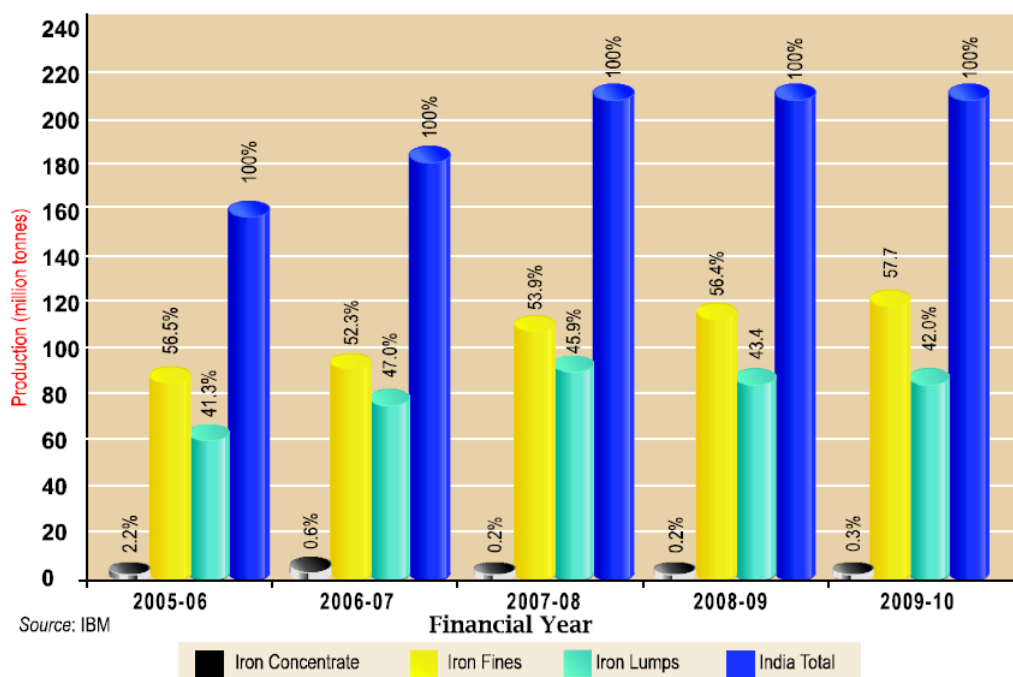
**TABLE 1**

<b>Mines Reporting Production :</b>				
	<b>No. of Mines</b>		<b>Production (Th. Tonnes)</b>	
	<b>2011-12</b>	<b>2012-13</b>	<b>2011-12</b>	<b>2012-13<sup>(B)</sup></b>
<b>INDIA</b>	<b>313(25)</b>	<b>270(14)</b>	<b>168582</b>	<b>136019</b>
Public Sector	36	34(1)	56610	52553
Private Sector	277(25)	236(13)	111972	83466
Captive	27	27	42967	44883
Non-captive	286(25)	243(14)	125615	91136
'A' Category	137(3)	116(2)	126514	103447
'B' Category	176(22)	154(12)	42068	32572
<b>STATES</b>				
Andhra Pradesh	40(4)	36(3)	1776	1111
Chhattisgarh	11	11	30457	27941
Goa	69(2)	43(2)	33636	10575
Jharkhand	19(1)	14(1)	19258	18010
Karnataka	67(7)	68	13233	11225
Madhya Pradesh	17(8)	14(5)	1237	1421
Maharashtra	14	11	1539	1193
Odisha	74(3)	71(3)	67414	64308
Rajasthan	2	2	32	235
<b>GRADES</b>				
<b>Lumps (Total)</b>			<b>62799</b>	<b>53888</b>
Below 55% Fe			7433	3184
55% to below 58% Fe			3184	1669
58% to below 60% Fe			2944	2725
60% to below 62% Fe			5501	3356
62% to below 65% Fe			25690	27867
65% Fe and above			18047	15087
<b>Fines (Total)</b>			<b>105383</b>	<b>81808</b>
Below 55% Fe			16824	8229
55% to below 58% Fe			8881	6037
58% to below 60% Fe			5993	3569
60% to below 62% Fe			19635	14869
62% to below 65% Fe			41139	35549
65% Fe and above			12911	13555
<b>Concentrates (Total)</b>			<b>400</b>	<b>323</b>



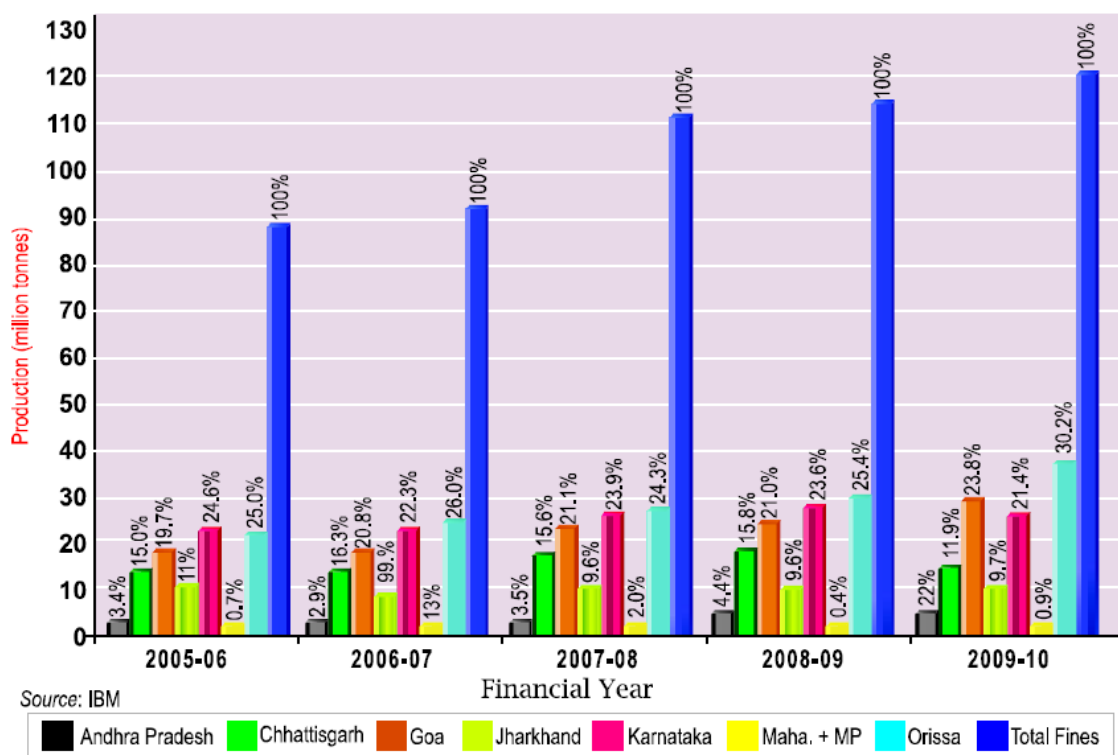
**fig 1**

**Figure 2** shows the comparison among production of Iron ore Fines, Lumps & Concentrate in India.



**Production of Iron Ore Lumps, Fines & Concentrates in India**

**Figure 3** shows the State wise Production of Iron ore Fines in India



**Statewise Production of Iron Ore Fines in India**

Source: Indian Bureau of Mines, Ministry of Mines, Govt. of India, Iron & Steel Vision 2020



## Coal Reserves of India <sup>[2]</sup>

India is having some of the largest coal reserves in the world (approx. 285 billion tonnes or 10% of the world). It is the third largest producer and has the fourth largest coal reserves in the world.

Indian coal is broadly classified into two categories – Coking and Non-Coking. Coking coal reserves in India amounts to 33474.26 million tonnes (12%) whereas non-coking coal reserves amounts to 250895.31 million tonnes (88%).

The coal reserves in India are widely distributed over 14 states in India located as far as Maharashtra in the west, Madhya Pradesh and Chhattisgarh in Central India, Tamil Nadu in the south and Assam in the northeast. However, the eastern states of West Bengal, Orissa, Jharkhand, etc. are the principal coal- bearing states in the country.

Indian coal generally has a low calorific value as well as high ash content (up to 35%) which are important parameters in governing the use of coal in making metallurgical coke to be used in blast furnace. Besides poor quality, Indian coal has adverse washability characteristics, i.e. even after undergoing extensive crushing before washing the removal of ash becomes difficult without a significant loss in yield. Record of geological resources of coal in india as on April 1, 2012 are given in Table 2.

Gondwana Coalfields				(In Million Tonnes)
State	Geological Resources of Coal			
	Proved	Indicated	Inferred	Total
Andhra Pradesh	9566.61	9553.91	3034.34	22154.86
Assam	0	2.79	0	2.79
Bihar	0	0	160.00	160.00
Chhattisgarh	13987.85	33448.25	3410.05	50846.15
Jharkhand	40163.22	33609.29	6583.69	80356.20
Madhya Pradesh	9308.70	12290.65	2776.91	24376.26
Maharashtra	5667.48	3104.40	2110.21	10882.09
Orissa	25547.66	36465.97	9433.78	71447.41
Sikkim	0	58.25	42.98	101.23
Uttar Pradesh	884.04	177.76	0	1061.80
West Bengal	12425.44	13358.24	4832.04	30615.72
<b>Total</b>	<b>117551.01</b>	<b>142069.51</b>	<b>32383.99</b>	<b>292004.51</b>

Tertiary Coalfields					(In Million Tonnes)
State	Geological Resources of Coal				
	Proved	Indicated	Inferred (Exploration)	Inferred(Mapping)	Total
Arunachal Pradesh	31.23	40.11	12.89	6.00	90.23
Assam	464.78	42.72	0.50	2.52	510.52
Meghalaya	89.04	16.51	27.58	443.35	576.48
Nagaland	8.76	0	8.60	298.05	315.41
<b>Total</b>	<b>593.81</b>	<b>99.34</b>	<b>49.57</b>	<b>749.92</b>	<b>1492.64</b>

**Table 2**

## Direct Reduction Procedure Of Iron Making

The DRI technique is one of the alternative methods of Iron making with excellent flexibility of consuming diverse kinds of reductants such as lower grade non-coking coal, natural gas ,char coal, etc. Direct reduced iron is manufactured from direct reduction of iron ore by a reducing gas manufactured either from natural gas or coal. This route produces 96% pure iron which is called solid sponge iron or direct reduced iron or hot briquetted iron.

The various processes of DRI technique based on coal and gas are: [1]

1. Coal based rotary kiln process.
2. Gas based shaft furnace process.
3. Coal/gas based rotary hearth furnace process.
4. Multiple hearth furnace based routes.
5. Coal based DR in Tunnel kilns.
6. Fluidised bed processes.

## Importance Of DR Process

The DR process of iron making is fast gaining importance in the country because it eliminates the dependence on coking coal and is cost effective. Irrespective of the DR process adopted, the cost of raw materials adds up to approximately 65-75% of the total cost of producing direct reduced iron. Hence to curtail costs, the trend in all the recently developed DR processes is to shift from lump ore to fine ore and to use the less-expensive energy resources like coal fines, waste gases, etc.

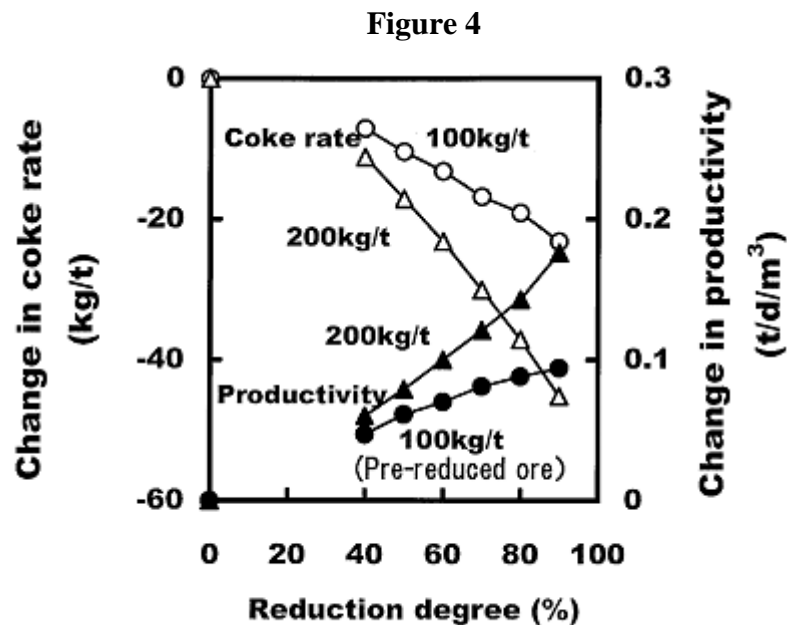
Advantages of DR process over blast furnace iron making process are: [5]

1. Exclusion of dependence on Coking-coal.
2. Smaller module size.
3. Minor capital investment.
4. Superior environmental friendliness.
5. Easy process control.

### Pre-Reduced Iron Ore [5]

It is likely to improve the flexibility and productivity of the BF and DRI process procedure and also to supplement energy sources in the pig-iron production by at least 20-35% bonding the partial reduction procedure consuming low-carbon content energy sources as natural gas with the BF process. Hence, the productivity of generating partially reduced ore, the composition of the in part reduced ore and the reducing agents rate in the blast furnace when the partially reduced ore was utilised were examined by Nippon steel.

It was observed that this process not only lessens energy intake in the present blast furnace iron making process, but also decreases the consumption of energy linked to CO<sub>2</sub> discharge in the total hot metal production processes, including the partial reduction procedure. The figure 4 shows the Influence of reduction degree of charged pre-reduced Fe-ore on coke-rate and productivity of BF.



## Production Of Direct Reduced Iron In India And World

The total worldwide production of DRI has reached 69.9 million tonnes in 2010 from of 7.8 million tonnes (20 years ago). It is clear from the Table 5 that the DRI production has increased and been on a growing trend. India is now the leading producer of DRI in the world with a production of around 25.34 million tonnes per annum.

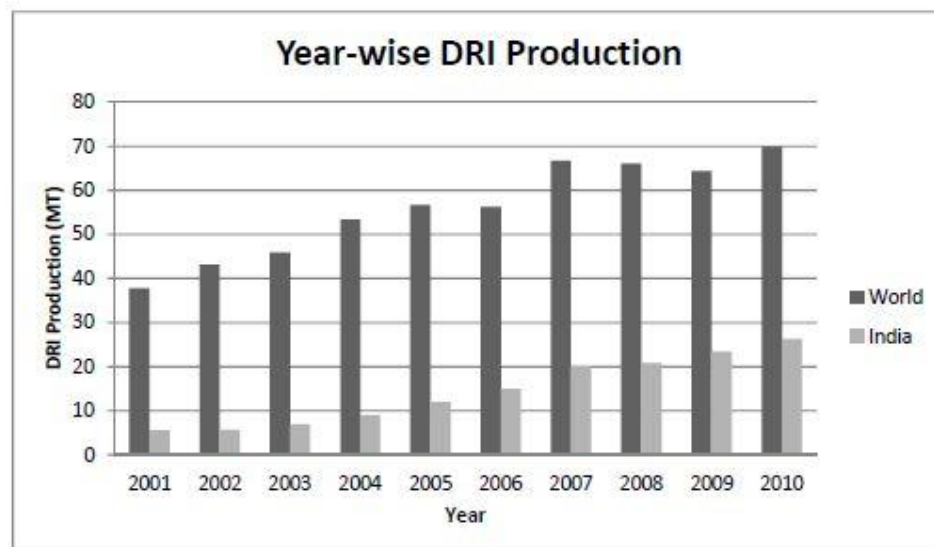
Out of the total DRI produced in India in 2010 around 19 million tonnes was produced in coal based units while the rest 7 million tonnes was produced in gas based units [8]. This large variance is due to the scarcity of natural gas and abundant supply of non-coking coal in India.

A year-wise production of Direct Reduced Iron in the world including India is given in Table 3.

**Table 3: Year-wise production of DRI in India and World**

Year	Production of DRI (In Million Tonnes)	
	World	India
2001	37.778	5.721
2002	43.18	5.732
2003	45.88	7.052
2004	53.438	9.123
2005	56.69	12.054
2006	56.376	15.031
2007	66.757	20.102
2008	66.093	20.915
2009	64.486	23.446
2010	69.951	26.307

Source: Steel Statistical Yearbook 2011, World Steel Association



**Figure 5**

## **OBJECTIVES OF THE PROJECT WORK**

The objectives of the present project work have been the followings:

1. To see the potential of utilization of -100# mesh size particles to a certain extent in the manufacture of pellets.
2. To develop an alternative binder to get a better substitute of costly bentonite. In the present work an attempt is made with concentrated Sucrose binder as an alternative binder.
3. To study physical properties (crushing strength, porosity etc.) of fired iron ore.
4. Pellets made under different circumstances.
5. To study the effect of reduction temp & time, on the reduction-behavior of fired iron ore pellets in non-coking coal.
6. To study the influence of quality of coal (reactivity) on reduction-behavior of fired Fe-ore pellets.

## LITERATURE SURVEY

During mining and ore dressing operations a large amount of (-0.5mm) fines are generated which cannot be sintered because of very low permeability of the bed. According to the industry the high grade domestic lumpy ore will be exhausted in the next 10 years. Because of these reasons value addition to the iron ore fines by various processes such as pelletisation is the need of the present scenario, which will be economically beneficial for the long run. The fines can be agglomerated by balling them up in the presence of moisture and suitable binders such as Bentonite, lime etc. into 8-20 mm or larger size. This process of agglomeration of fines is known as pelletisation. These green pellets are further hardened by firing at temps of 1200-1350 °C

### Mechanism Of Pelletisation

The formation of pellets consists of two processes – Ball formation and Induration (Heat Hardening).

**Ball Formation** – Surface tension (S) of water and gravitational force generates pressure on particles, so they blend together and form nuclei which grows in size into ball.

**Induration (Heat Hardening)** – Solid state diffusion take place at particle surfaces when the balls are subjected to higher temp causing recrystallization and growth. This process provides strength to the green pellets.

### Advantages Of Pellets

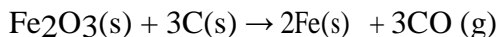
1. Very good reducibility because of high micro-porosity (25-35 %)
2. Spherical shape and uniform size give very good bed permeability
3. High strength (about 150-250 kg) or more for acid pellets
4. Heat consumption is much less than that of sintering.
5. High Iron content and uniform chemical composition hence lower flux and fuel requirement in the furnace.
6. Ease of handling

### Disadvantages associated with Pellets

1. High cost to manufacture due to firing and grinding
2. Loss of strength & swelling in the furnace
3. Difficulty in producing fluxed pellets
4. Opposition to the gas flow more than gas flow in sinter for same sized , due to lesser void ratio.

## **Thermodynamics And Kinetics Of Iron-Oxide**

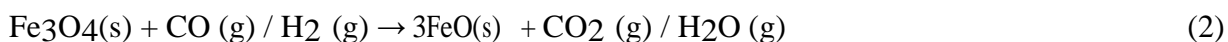
### **Chemical reactions involved**



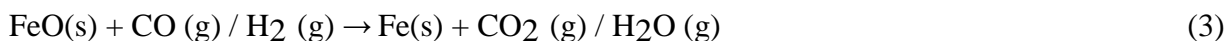
### **Reduction of Hematite**



### **Reduction of Magnetite**



### **Reduction of Wustite**



### **Other possible reactions**



It can be said that the most feasible reaction is (1), trailed by reactions (2) and (3). The reactions (4) and (5) are very endothermic and likely only at high temp. In contrast to CO gas, the reactions of reduction with H<sub>2</sub> gas are generally favoured at elevated temperatures and thus are endothermic.

### **Steps involved in Reduction Kinetics**

#### **Before the formation of Metallic Layer**

The kinetics involved in reduction of hematite iron ore by CO/H<sub>2</sub> gas are as follows:

- Transportation of CO/H<sub>2</sub> gas from bulk gas phase to Fe<sub>2</sub>O<sub>3</sub> - CO/H<sub>2</sub> interface.
- Adsorption of CO/H<sub>2</sub> gas at the Fe<sub>2</sub>O<sub>3</sub> - CO/H<sub>2</sub> interface.
- Chemical reaction between Fe<sub>2</sub>O<sub>3</sub> and CO/H<sub>2</sub> gas at the Fe<sub>2</sub>O<sub>3</sub>- CO/H<sub>2</sub> interface and desorption of the product gas CO<sub>2</sub>/H<sub>2</sub>O from this interface.
- Transportation of product gas from Fe<sub>2</sub>O<sub>3</sub>- CO/H<sub>2</sub> interface to the bulk gas phase.

#### **After the Formation of Metallic layer**

- Transportation of CO/H<sub>2</sub> gas from bulk gas phase to the Fe-CO/H<sub>2</sub> interface.
- Adsorption of CO/H<sub>2</sub> gas at the Fe-CO/H<sub>2</sub> interface.
- Transportation of CO/H<sub>2</sub> gas from Fe-CO/H<sub>2</sub> interface to the Fe<sub>2</sub>O<sub>3</sub>-Fe interface.
- Chemical reaction between Fe<sub>2</sub>O<sub>3</sub> and CO/H<sub>2</sub> at Fe<sub>2</sub>O<sub>3</sub>-Fe interface.
- Desorption of the product gas CO<sub>2</sub>+H<sub>2</sub>O from this interface.

- f. Transportation of  $\text{CO}_2/\text{H}_2\text{O}$  gas from  $\text{Fe}_2\text{O}_3\text{-Fe}$  interface to  $\text{Fe-CO}/\text{H}_2$  interface
- g. Transportation of the product gas from  $\text{Fe-CO}/\text{H}_2$  interface to the bulk gas-phase.

The steps involved are either *diffusional* or *chemical* and the slowest of these control the overall rate of reaction.

### **Factors Affecting the Rate of Reduction**

- 1. Temp of reduction
- 2. Time of reduction
- 3. Pellet Size
- 4. Presence of catalyst
- 5. Reactivity of coal
- 6. Chemical nature of ore

### **Factors Responsible For Swelling of Fired Fe-Ore Pellets**

Pellets in the reduction furnace swell and hinders its operation. Two main disadvantages of swelling are: reduced strength and disintegration of compact during reduction. However an increase in volume up to 20% is tolerable and is considered as normal swelling which is the characteristics of compact. As in literature the reasons for swelling as proposed are:

- 1. Degradation of Iron grains
- 2. Whisker or Fibrous growth of iron
- 3. Crack generated during reduction
- 4. Recrystallization of iron grains
- 5. Structural changes during reduction
- 6. Physical properties of pellets (crushing strength, porosity etc.)
- 7. Briquetting parameters (fine size, Compaction pressure, binders etc.)
- 8. Firing parameters (temp, time etc.)
- 9. Reduction parameters (mode of heat, gas composition, time, temp)

#### **Degradation of Iron grains**

Swelling can be as high as 130% without whisker formation, when reduced up to temp about  $900^0\text{C}$ , which is explained as: carbon deposition and consequent emission of large amount of  $\text{CO}/\text{CO}_2$  gases, causing expansion and disintegration of iron grains [7]. However at such a high temp



about 1100<sup>0</sup>C, disintegration decreases and completely disappeared due to recrystallization.

### **Whisker or fibrous growth of iron**

Most of the researchers in their work claimed whisker or fibrous growth of iron grains as the major cause of swelling behaviour observed during reduction [8][9][10][11][12]. In the recent study, the dense whiskers and plates in porous structure are formed during abnormal swelling in fired hematite compact.

### **Crack generated during reduction**

Inter-granular and trans-granular cracks are generated during reduction are responsible for the change in volume of iron ore pellets during the transformation from hematite to wustite when swelling is marked as 20-27% [13]. Cracking in the pellets is also due to the combined effect of thermal and volume strains (lattice disturbance) during the transformation from hematite to wustite<sup>[14]</sup> [10]. Growth of iron whiskers favoured by cracks and voids generated.

### **Recrystallization of iron grains**

Sintering is favoured by greater degree of metallization, high reducing temp and large amount of whiskers formation which further lead to shrinkage. The newly formed iron surface is more reactive and has a greater tendency to stick together because of high energy [15]. The sticking tendency of particles is mainly due to adhesive force, area of contact, and pellet's iron content, however greater will be the size and its mass higher will be the momentum, henceforth lower will be the agglomeration [16].

### **Structural changes during reduction**

Sintering of iron ore pellets results and its volume change is mainly due to the changes in crystal structure during reduction. During the first stage of reduction hexagonal hematite lattice converts into cubic magnetite lattice and results in about 25% increase in volume [16]. However lattice remains unchanged and is accompanied by a small increase (7-13%) in volume during the transformation of magnetite to wustite.

### **Physical Properties of Pellets**

Crushing strength and porosity of pellets more strongly influence its swelling characteristics than

geometry [12][17]. Also with increase in crushing strength and decrease in its porosity, the swelling index of pellets decreases. Lower crushing strength and higher porosity gives more active sites for nucleation and evolution of iron whiskers. The high strength of pellets is mainly due to presence of slag bonds, these whiskers hence, are unable to push mechanically the grains adjacent to it and therefore results into decrease in volume (lower swelling) [10][18][19][20]. However according to some studies pellets having higher porosity indicates less swelling because more stresses can be accommodated which is produced during the course of reduction and formation of iron whiskers [21].

### **Briquetting parameters**

Addition of gangue such as MgO, SiO<sub>2</sub>, CaO, Al<sub>2</sub>O<sub>3</sub>, bentonite, molasses etc. reduces the growth of iron whiskers and hence puffiness of iron ore pellets during reduction, which is further explained as addition of these constituents increases its crushing strength and hence do not allow the iron ore whiskers to grow sufficiently during reduction, as a result lower swelling is obtained [22] [23] [12] [24] [19][7]. Sequence of constituents, decreasing the swelling indices of fired up Fe ore pellets is MgO, followed by silica, lime and alumina [18].

### **Firing parameters**

With increase in firing temp the swelling index of iron ore pellets decreases [24] [12] [25] [18]. It is observed that pellets which are fired at high temps and for a longer time has higher crushing strength and porosity, due to formation of slag bonds and which resulted into reduced growth of iron whiskers and thus lower swelling. A decrease in number of sites for growth of iron whiskers is observed when it is fired at a high temp, which resulted into decrease in swelling index of iron oxide compact [26].

### **Reduction Parameters**

Iron oxide compacts reduced with CO gas shows a gradual increase in swelling up to a maximum of 176% with rise in temp up to 900<sup>0</sup>C, which further decreases with increase in temp up to 1100<sup>0</sup>C [7]. Decrease in volume (lower swelling) at higher temp was due to sintering and recrystallization of Fe grains, whereas carbon deposition and disintegration of iron grains are the main reasons for increase in volume up to 900<sup>0</sup>C [4]. Higher swelling in the temp range of 900-1000<sup>0</sup>C and shrinkage in the range 1100-1200<sup>0</sup>C is found while working on reduction of hematite or magnetite iron ore pellets comprising char. In the temp range of 700-1000<sup>0</sup>C swelling increases with reduction temp and is maximum at

around 900-950<sup>0</sup>C [21] [7]. During reduction of iron oxide compacts by CO gas in the range 800-1100<sup>0</sup>C and it was found that swelling reaches a maximum value at about 900<sup>0</sup>C due to larger amount of whiskers at this temp [26]. Reducing gas containing hydrogen accelerates the rate of reduction and hence reduces the chances of whisker growth [14] [28] [26]. Gas-solid reaction on the iron oxide surface is inhibited due to adsorption of sulphur on it.

## EXPERIMENTAL DETAILS

### Selection of Materials

In this work hematite iron ore was obtained from Sakaruddin mines of Orissa and its physical and chemical characteristics are detailed in Table 4, 5 and 6. Low grade (F) non-coking and other coal used in the study are obtained from various mines and examined for their proximate analysis (IS : 1350 : 1969), reactivity towards CO<sub>2</sub> gas (IS : 12381: 1994), ash fusion temps (DIN : 51730 : 1984) and caking index (IS : 1353 : 1993). The results obtained have been listed in Table 5 and 6.

**Table 4: Chemical composition of Fe Ore obtained from Orissa, India (wt. %, air-dried basis)**

Fe (total)	Fe <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	TiO <sub>2</sub>	MnO	Loss on Ignition
64.53	91.4	3.09	1.51	0.17	0.03	3.57

**Table 5: Physical Properties of Fe Ore obtained from mine of Orissa, India (wt. %, air-dried basis)**

Tumbler Index (wt. % of +6.3mm)	Abrasion Index (wt. % of -0.5mm)	Shatter Index (wt. % of -5.0mm)	Apparent Porosity (%) Lump Ore	Apparent Porosity (%) Fired Pellets
92.79	4.82	0.59	1.5	18.7

**Table 6: Mechanical properties of Iron Ore Pellets**

Binder	Binder (%)	Firing Conditions		Crushing Strength (Kg/pellet)	Porosity
		Firing Temp (°C)	Firing Time(hr)		
Concentrated Organic Binder	1	1100	1	840	8.1
	2	1100	1	925	8.5
	3	1100	1	637	15.2
	4	1100	1	215	20.5
	6	1100	1	140	27.2
	8	1100	1	105	31.9

**Table 7: ash fusion temperatures of non-coking coal, Chemical composition, reactivity, caking index procured from Ananta mine of Orissa, India**

Proximate analysis (wt.%, dry basis)			Sulphur content (wt. %)	Reactivity (cc of CO/g. of C/sec.)	Caking index	Ash fusion temperatures( <sup>0</sup> C)			
Volatile matter	Ash	Fixed carbon				IDT	ST	HT	FT
26.2	40.1	33.7	0.4	5.92	Nil	1318	1506	1602	1645

**Table 8: Characteristics of coal selected (proximate analysis) in present study**

Type of Coal	Moisture (%)	Ash (%)	Volatile Matter (%)	Fixed Carbon (%)	Reactivity (cc of CO/g of C. sec)
Sample-A	4	27	4	65	2.9
Sample-B	3	20	7	70	3.68
Sample-C	3.5	31.5	5	60	3.05

## Sample Preparation

The Iron ore fines -100 mesh size approx. 84%, -16+25 mesh size approx. 16% were thoroughly mixed with the addition of concentrated Sucrose binder as binder with varying amount as 2%, 4 %, 6% and little amount of water in it. Pellets are then made by Hand Rolling method. The pellets are dried in electric oven at 110 <sup>0</sup>C for more than 5 hours. The dried pellets were fired by firing them inside the muffle furnace starting from room temp to 1100<sup>0</sup>C at a rate of around 4<sup>0</sup>C/min and soaking at this temp for around 1 hour, then cooling in furnace.

## Reduction Behaviour

Separate reductions were carried out in coal fines of -4+6 mesh size. In this study, single type reduction experiments, on the fired iron ore pellets ( W e i g h t e d ) which were centrally embedded inside the crammed bed of coal particles in each of stainless steel reactors (size: 75mm in height x 40 mm in diameter), have been performed by heating the reactors from room temp to the predetermined temp of 950<sup>0</sup>C, 1000<sup>0</sup>C at a rate of about 4<sup>0</sup>C/min. Each of the reactor was closed with

a cover (air tight) with a vent for the release of gas. The temp was controlled in  $\pm 5^{\circ}\text{C}$ . After soaking for predetermined period of time the reactors were pulled out of the furnace after an interval of 15 minutes and cooled to room temp in air. The reduced pellets are weighed and the degree of reduction is calculated by wt. % of  $\text{O}_2$  removed from each of them.

Using Vernier Callipers the diameter of the pellet before and after reduction are measured thrice each and averaged to determine volumes. The swelling-shrinkage at different time slots of reduction was calculated, using the formula:

$$\text{Swelling index (\%)} = \{(V_f - V_i)/V_i\} \times 100$$

Where,

$V_i$ – Initial Volume of Pellet, and

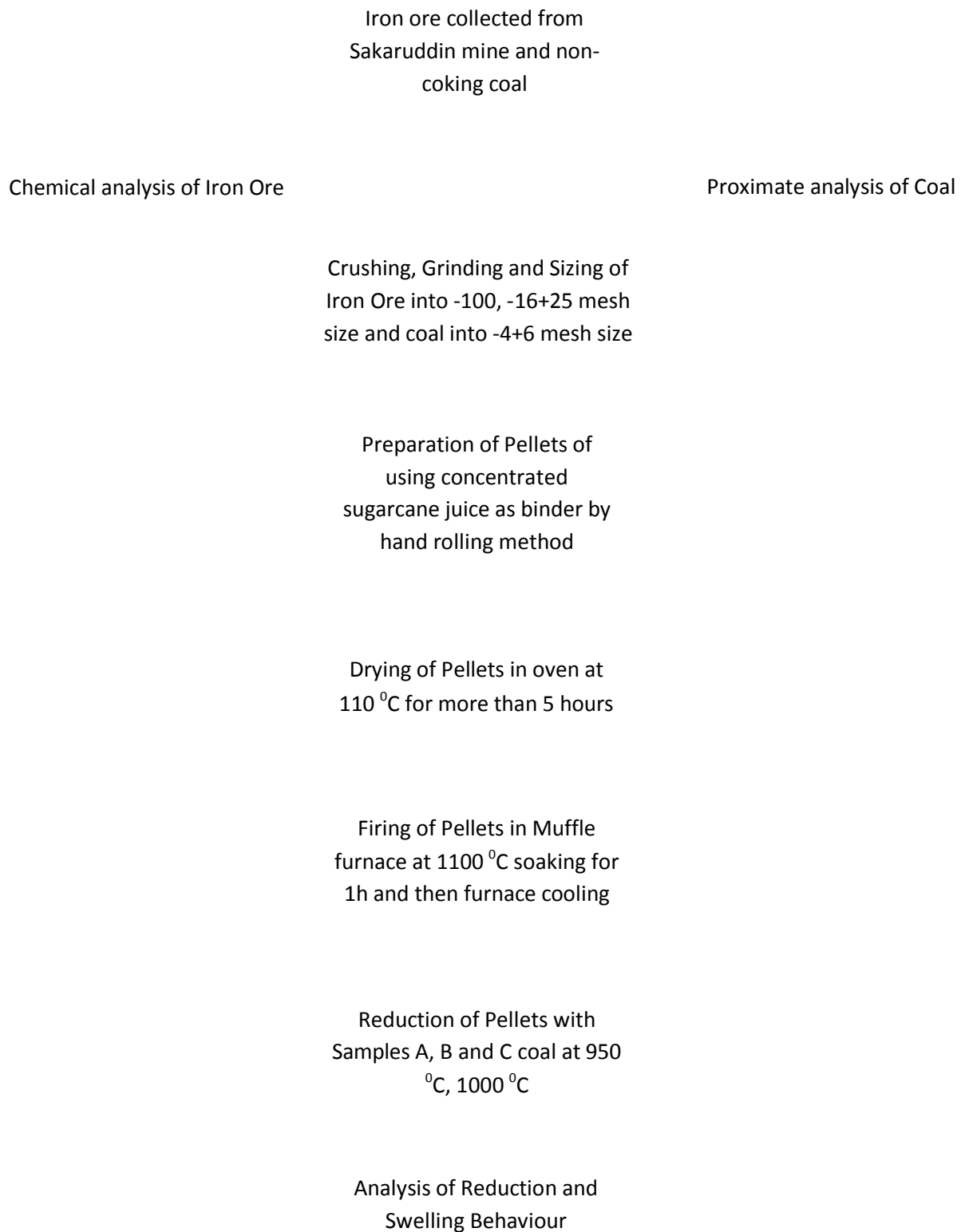
$V_f$  – Final Volume of Pellet after reduction for a given time.

Weight losses in pellets were recorded by an electronic balance to calculate to calculate the Degree of Reduction.

Degree of Reduction was calculated by following formula:

$$\text{Degree of Reduction} = (\text{Weight loss in pellets} / \text{total oxygen content in the pellets}) \times 100$$

## ***Process Flow Chart:***



## **RESULTS AND DISCUSSION**

### **Characteristics of Iron Oxide Feed Suitable For Use In Rotary Kiln**

In general, the oxide feed (hematite and magnetite) must have iron content more than 62% and the allowable amount of silica plus alumina should not exceed 4% for producing sponge iron as shown in Table 9. Iron ores with Fe contents  $> 66\%$  are not easily reducible and higher amount of FeO is retained in the produced DRI. While ores of lower grade (Fe content: 62 – 66%) are likely to be more suitable for sponge iron production. Higher (TiO<sub>2</sub>) content may have a deleterious effect on the reducibility of the oxide feed and hence, a lower degree of metallization could be achieved in the reduced product. In general, the (TiO<sub>2</sub>) content in the oxide feed should not exceed 0.15% (Table 6)

In general, coals with high reactivity values are preferred as they allow kiln operations at comparatively lower temps with improved productivity and decreased tendency towards ring-formation.

Another important characteristic of coal is the primary deformation temp (IDT) of its ash. In order to ensure no agglomerate formation in the charge bed, the caking index of coal should be preferably under 1 (however, tolerable up to 3). However, lesser fixed carbon and higher ash contents in this coal may increase its consumption during DRI production in rotary kiln.

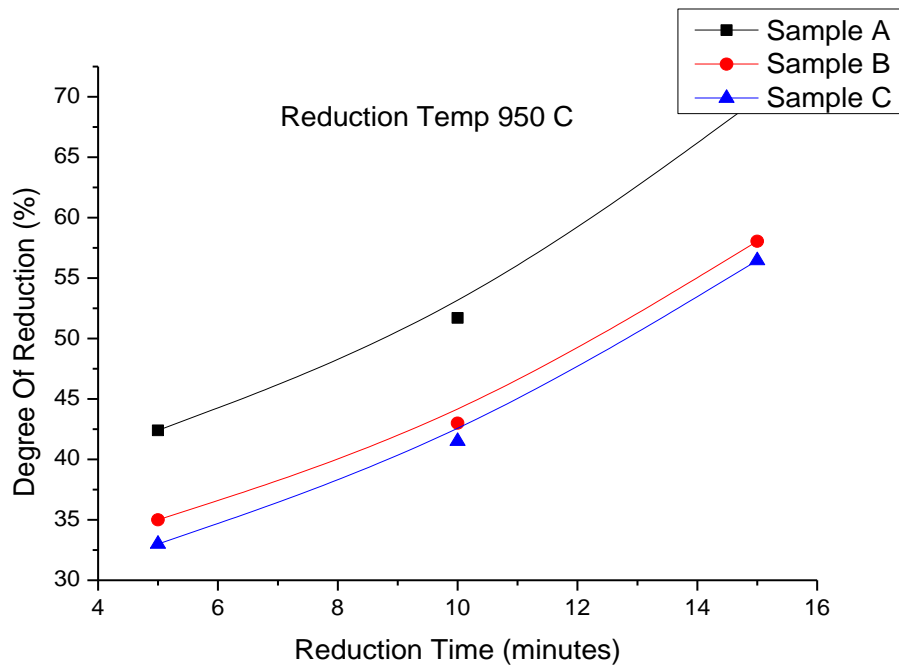
### **Reduction Behaviour of Fired Fe Ore Pellets**

Data on the degree of reduction Vs time (Table 11) for fired iron ore pellets, reduced in sample A,B and C coal (size: -4+6 mesh size) at temps of 950 and 1000 C, are presented graphically in figure 6 and 7 as below.



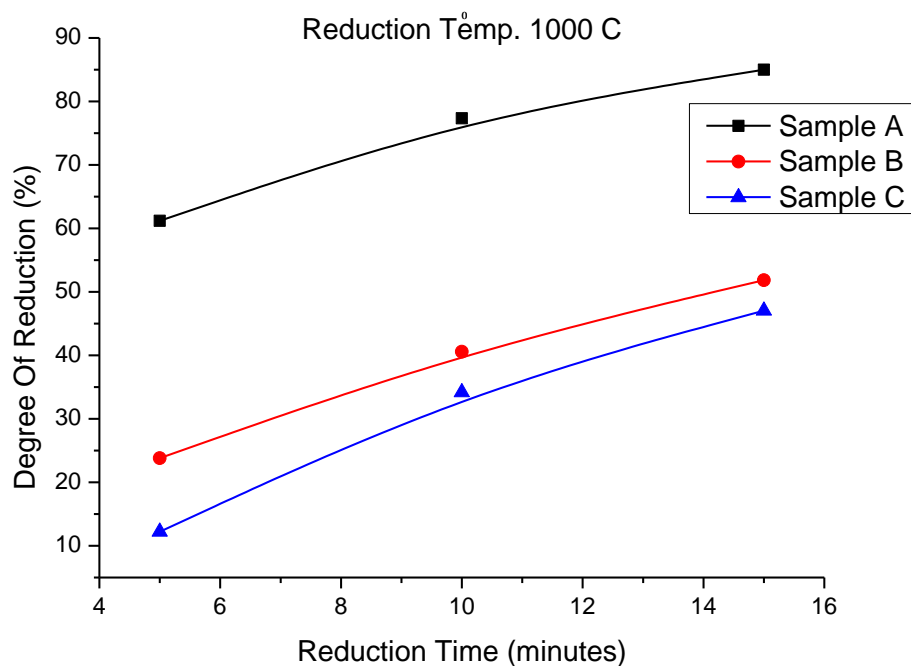
**Table 9: Reduction Characteristics of Fired Iron Ore Pellets**

Binder	Binder (%)	Reduction Temp (°C)	Coal Type	Time (min)	Degree of Reduction (%)
Concentrated Sucrose binder	2	950	Sample A	5	42.4
				10	51.7
				15	69.8
			Sample B	10	43
				15	58.05
			Sample C	10	41.5
				15	56.46
		1000	Sample A	5	61.2
				10	77.33
				15	84.99
			Sample B	5	23.8
				10	40.57
				15	40.57
			Sample C	5	12.21
				10	34.18
				15	47.03



**Figure 6**

**Figure 6: Degree of Reduction vs. Time graphs for the reduction of fired Fe Ore Pellets fired at 1100°C and reduced in coal (-4+6 mesh size) at a temperature of 950°C.**



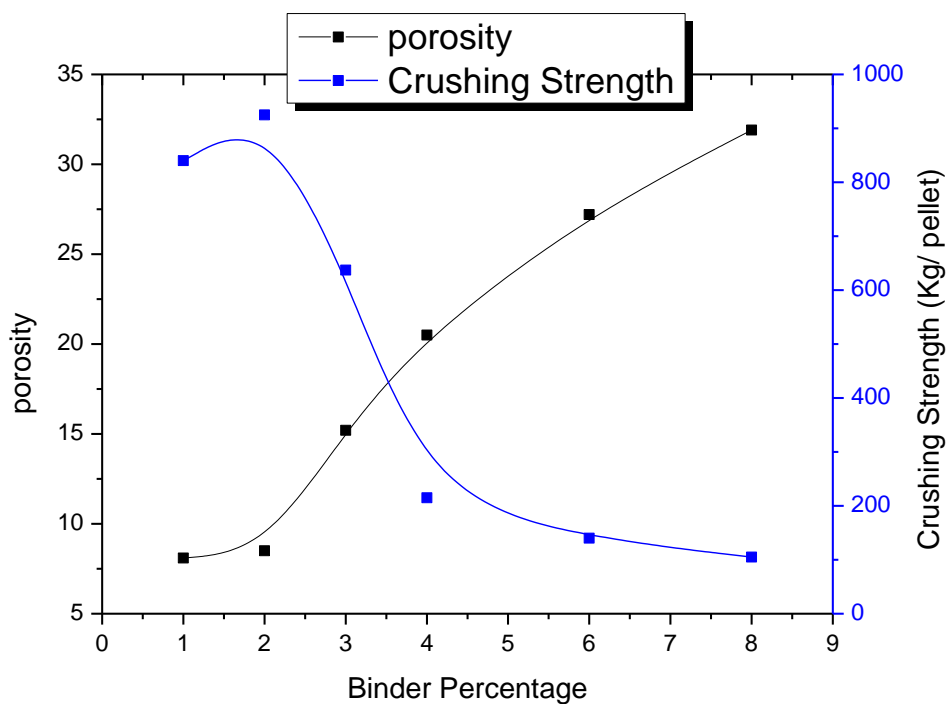
**Figure 7: Degree of Reduction vs. Time graphs for the reduction of fired Fe Ore Pellets fired at 1100°C and reduced in coal (-4+6 mesh size) at a temperature of 1000°C**

The results (figure 6 and 7) shows that in all the studies of fired iron ore pellets, the reduction rate improved significantly with increase of temp. up to (950°C, 1000°C). As shown in this figure, the degree of reduction also increases with time at all the studied temps.

### Effect of Binder %

It is observed from the experiments that crushing strength decreases with increase in binder %, as shown in figure 8. **Figure 8:**

**Porosity & Crushing Strength vs. Binder (%)**



## Effect of Coal Reactivity

It is also observed from the experiments that the extent of reduction depends on reactivity of Coal which is depicted graphically in the figure 9.

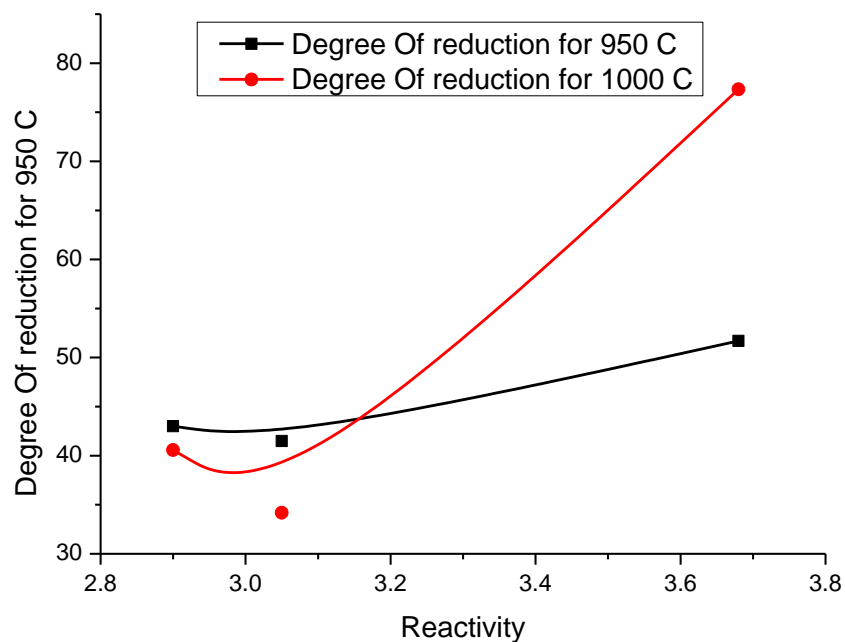


Figure 9

## Effect of Coal Chemistry

Figure 10 shows the variation of degree of reduction with respect to Volatile matter content.

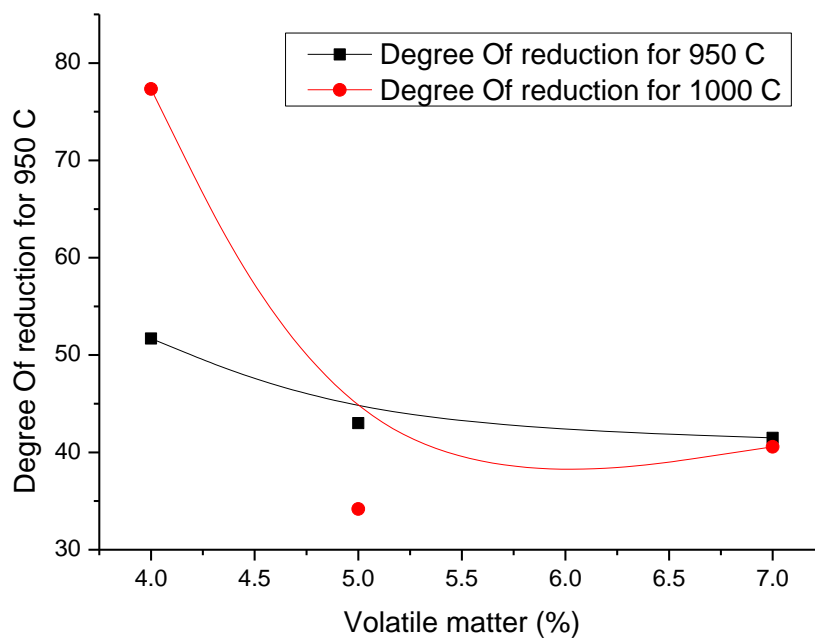


Figure 10

## CONCLUSIONS

- i. The crushing strength of the fired Fe-ore pellets decrease with the addition of concentrated Organic binder from 2% to 8%.
- ii. The porosity of the fired Fe-ore pellets increase with the addition of concentrated Organic binder from 2% to 8%.
- iii. The degree of reduction grows with growth in temp in the studied temp range (950 – 1000<sup>0</sup>C).
- iv. The degree of reduction of the pellets increases with rise in reduction time up to the range studied.
- v. The degree of reduction of fired Fe-ore pellets increased with increase in the reactivity of the coal.
- vi. There was increase in reduction percentage of the fired iron ore pellets with rise in reduction time.

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